sub A1

TITLE: Angle Random Walk (ARW) Noise Reduction in Fiber Optic Sensors using an Optical Preamplifier

INVENTOR: Sidney M. Bennett

Field

This invention generally relates to fiber optic sensors, and more specifically to using optical preamplifiers to improve Angle Random Walk noise in fiber optic sensors by increasing the optical power at a detector of the fiber optic sensor.

Background

The angle random walk noise (ARW) of a fiber optic sensor, such as a fiber optic current sensor or fiber optic gyroscope, is comprised of noise arising from the transimpedance amplifier feedback resistor (thermal noise), shot noise related to the detector current, and flicker (1/f) and relative intensity noise (RIN) intrinsic in the light impinging on the photodetector. The first is independent of the light power, the second can be shown to be proportional to the square root of optical power, and the last two (flicker, RIN) are proportional to the optical power. What this means is that for any given sensor configuration (coil length, diameter, light source power, etc.), the effects of thermal and shot noise will decrease with increasing optical power, while the flicker noise and RIN effects cannot be reduced by increasing the optical power. For convenience, RIN will be used hereafter to refer to both flicker noise and true RIN effects.

The noise components in the sensor output can be represented as:

$$N = k\,(A^2P^2 + B^2P + C^2)^{1/2} \qquad \text{Eq. (1)}$$

where A is the RIN noise;

B is the shot noise;

C is the thermal noise;

P is the optical power at the detector; and

k is a proportionality constant.

The output signal of an open-loop fiber optic gyroscope (FOG) for small rotation rates is

$$S = m\phi\Omega P, \qquad \text{Eq. (2)}$$

where

Ω is the angular rotation rate;

m is a proportionality constant;

$\phi = 4\pi RL/c\lambda$ is the Sagnac or optical scale factor;

R is the radius of the equivalent coil; and

L is the coil length.

Thus, the signal-to-noise ratio is:

$$S/N = m\phi\Omega/(k\,(A^2 + B^2/P + C^2/P^2)^{1/2}), \qquad \text{Eq. (3)}$$

and the shot and thermal noise components decrease as the optical power is increased. However, the contribution of RIN to the signal-to-noise is unchanged and the performance of a FOG with

conventional signal processing ultimately becomes limited by RIN. Usually the thermal noise component can be ignored.

Fig. 5 illustrates the dependence of the individual noise components as a function of detected optical power. (Lefevre, "The Fiber-Optic Gyroscope", Artech House, Boston 1993). The inverse of the signal-to-noise ratio or relative noise is shown on the ordinate and is called the "Angle Random Walk" (ARW). This can be interpreted as the minimum detectable rotation signal when normalized to a one Hz bandwidth. In Fig. 5, "source noise" represents the RIN.

The reduction of RIN is addressed in "Apparatus and Method for Electronic RIN Reduction in Fiber-Optic Sensors", by Bennett, U.S. Patent Application Ser. No. 09/481,159. Here we look at the shot noise for situations where either the RIN had been reduced to the point where shot noise is dominant, or situations where the detected power is low enough so that the shot noise can be considered the dominant component. (In the context of Fig. 5, a region where shot noise is dominant exists between optical powers of 10^{-5} and 10^{-4} watts.). To simplify the discussion, we will assume that shot noise is the only noise present.

Shot noise arises from the interaction of individual photons in the light beam incident on the detector with the physical matter of the detector itself. The effect is quantized in nature so that some number (which could be fractional) of electrons is liberated for each photon impinging on the detector in a spectral regime where the detector exhibits a photoelectric effect.

From this discussion, it can be seen that the concept of detected signal-to-noise differs fundamentally from that employed in radio reception systems. In those systems, the noise power is not a function of the input signal, and signal-to noise ratio increases linearly with signal power.

Even in optical telecommunications systems, where the thermal, shot and RIN noise components are present, RIN noise can be reduced by limiting the bandwidth of the optical signal at the input to the photodetector to that required by the modulation bandwidth by optical bandlimiting. In a fiber optic sensor, this is not possible, as a broad optical bandwidth (usually greater than several nanometers) is necessary to overcome certain deleterious optical effects, such as polarization cross-coupling and Rayleigh scattering.

The component of ARW due to shot noise can be reduced, by increasing the optical power at the detector. This is done in existing art by increasing the optical power emitted by the optical source, which may be a superluminescent diode (SLD), a semiconductor laser operated below threshold, a laser modified as in "Broadening the Linewidth of a Semiconductor Laser" by Dyott, U.S. Patent Application No. 09/568,371 which is incorporated herein be reference, or a rare-earth-doped fiber amplifier. This is usually done in the so called "minimum configuration" (MC) fiber optic gyroscope, but may also be done in the "Reduced Minimum Configuration" (RMC) device ("Monomode Optical Fiber Ring Interferometric Device with Semiconductor Diode as Light Energy Emission Reception/Amplification Means", U.S. Patent No. 4,842,409 to Arditty, et al. and "Reduced Minimum Configuration Interferometric Fiber Optic Gyroscope with Simplified Signal Processing Electronics", U.S. Patent Application Ser. No. 09/459,438 by Emge et al.). High power optical sources are known and used, but the cost of these devices increases substantially as the optical power is increased, and the reliability also is reduced due to various damage mechanisms that arise at high optical power densities. It is also known that the fiber exhibits a number of non-reciprocal effects and non-linearities at high optical powers, which can lead to degradation of other desired properties such as bias stability and scale factor.

Summary

According to the systems and methods disclosed herein, a shot noise component of Angle Random Walk noise in a fiber optic sensor may be reduced by providing an optical amplifier between a first coupler receiving a sensor signal from a sensing coil of the sensor and a photodetector receiving the sensor signal from the first coupler.

Another embodiment may further comprise providing a second detector on a free leg of the first coupler to receive a source sample from an optical source of the fiber optic sensor; delaying the source sample to provide a delayed source sample coinciding with the sensor signal; modulating the delayed source sample to provide a modulated source sample; and comparing the modulated source sample with the sensor signal so as to subtract Relative Intensity Noise.

Another embodiment may further comprise providing an isolator between the first coupler and the optical amplifier to suppress back facet emissions of the optical amplifier reaching the first coupler.

Another embodiment may further comprise: providing an additional coupler between the optical amplifier and the isolator; providing a third detector on a first leg of the additional coupler to receive the back facet emissions from the optical amplifier; and subtracting the back facet emissions received at the third detector from the sensor signal received at the photodetector.

A still further embodiment further comprises providing a polarizer immediately adjacent one or more of the detectors to preclude emissions in an unwanted polarization from reaching the detector to which the polarizer is adjacent.

Brief Description of the Drawings

The above-mentioned and other features will now become apparent by reference to the following description taken in connection with the accompanying drawings, in which like reference numerals refer to like elements. The depicted embodiments are to be understood as illustrative and not as limiting in any way.

Fig. 1 illustrates a Minimum Configuration (MC) fiber optic gyroscope having an optical amplifier;

Fig. 2 illustrates an embodiment of a fiber optic gyroscope having a second detector;

Fig. 3 illustrates a further embodiment of a fiber optic gyroscope having an isolator;

Fig. 4 illustrates another embodiment of a fiber optic gyroscope having an additional coupler and detector; and

Fig. 5 is a graph illustrating the relationship between optical power at the photodetector and noise components.

Detailed Description of the Preferred Embodiment(s)

Fig. 1 illustrates a minimum configuration (MC) fiber optic gyroscope 10, having an optical source 12, providing an optical signal or beam on fiber 14. At first directional coupler

16, a portion of the signal may be directed through linear polarizer 18 and to second directional coupler 20, where the signal may be split and directed into opposite ends of fiber optic coil 22 as counterpropagating beams. The counterpropagating beams may then be modulated at phase modulator 24. The beams exit coil 22 and combine/interfere at second coupler 20. The combined beams may then pass through polarizer 18 to first coupler 16, where a portion of the beam may be directed towards detector 26. In the embodiment of Fig. 1, according to the present invention, optical amplifier 28 can be interspersed between first coupler 16 and detector 26.

MC fiber optic gyroscopes constructed in the manner of Fig. 1, but without optical amplifier 28, are known in the art. A prior art MC fiber optic gyroscope of this sort may have an insertion loss between the source 12 and detector 26 of approximately 15 dB, i.e., a factor of 32. So, the optical power at the detector 26 may be reduced by this amount with respect to that which obtains at the source 12. With optical amplifier 28 inserted in the fiber immediately preceding the detector 26, the signal power can be increased by the gain factor G of the amplifier, and the ARW reduced.

For example, if the gain of the optical amplifier 28 was equal to that of the loss in the optical circuit, the ARW would be reduced by a factor of approximately 5.6 (i.e., $\sqrt{32}$), were the shot noise the only noise present. Alternatively this could have been achieved by an increase in the optical source output power by a factor of 32.

Optical amplifier 28 can be of the form of a Semiconductor Optical Amplifier (SOA), rare-earth-doped fiber amplifier, or similar optical amplification medium. The amplifier 28

bandwidth can be comparable to that of the optical source 12 and desirably can have a similar variation of central wavelength with temperature.

SAT 1-15-03

As is known, optical amplifiers can be the equivalent of Fabry-Perot lasers whose end face reflectivity is sufficiently low that lazing does not occur. Providing that the following inequality can observed, $G_s/\ (R_1R_2)<0.17$, where R_1 and R_2 are the reflectivities of the two facets and G_s is the single pass internal gain, the ripple in the amplifier passband can be less than 3 dB (High Speed Optical Communications, R. Sabella and P. Lugli, Kluwer Academic Publishers, 1999). Such amplifiers may sometimes be called traveling wave optical amplifiers (TWA). The term SOA as used herein may include the TWA. Optical amplifiers may often be polarization sensitive, so, it may be preferred to use a polarization insensitive configuration, or the coupler 16 used to isolate optical source 12 and detector 26 may be of the polarization maintaining type and the light energy of the MC fiber optic gyroscope 10 may be oriented in the axis of maximum optical amplifier 28 gain.

Optical amplifiers, such as optical amplifier 28, emit broadband energy similar to the broadband energy emitted by optical source 12, which, in the case of optical source 12, is used as the sensing energy in gyroscope 10. Optical source 12 energy passes through coil 22, and both senses rotation and is modulated by the phase modulator 24 such that it can be distinguished, by a frequency dependent detection technique, from the steady energy emitted from source 12. The broadband output of the optical amplifier 28 in the forward direction (i.e., towards the photodetector 26) does not pass through the sensing circuit, or coil 22, and carries no information related to the rotation. However, this energy creates both shot noise arising from its own photon stream and, due to its optical bandwidth, spontaneous beat noise arising from the demodulation

of the optical components due to the square law property of the photodector. The latter noise is equivalent in nature to the RIN arising from the broadband nature of the gyro optical sources. Methods of reducing RIN are discussed in Bennett, U.S. Patent Application Ser. No. 09/481,159, and references cited therein.

The design of the gyroscope 10 should minimize the contributions of the amplifier noise sources to the overall gyroscope noise as these will reduce the improvement arising from the amplification. However, the spontaneous emission of optical amplifier 28 in the backward direction (i.e., in the direction from amplifier 28 to coupler 16) passes through the coil 22 and is returned as a modulated signal containing information about the gyroscope rotation rate, essentially identical to that which was imparted to the optical signal or beam from the optical source 12. This signal is amplified in optical amplifier 28 and detected by the photodetector 26. The spontaneous emission of amplifier 28 is not correlated with that of the optical source 12. Hence the power in the two signals will add without changing the relationship of the amplitudes or phases in the spectral components. If the gyroscope signal at the photodector 26 arising from amplifier 28 spontaneous emission, which has passed through fiber coil 22, is comparable to or greater than that due to the optical source 12, a further improvement in ARW may be obtained as the effective signal power has been further increased. Alternatively, as discussed below, an optical isolator can be inserted between amplifier 28 and coupler 16, permitting the optical signal from the gyroscope to pass through to amplifier 28 and detector 26, but blocking light transmission in the reverse direction.

Referring now to Fig. 2, there is shown fiber optic sensor 50, including optical source 12, fiber 14, couplers 16, 20, polarizer 18, coil 22, phase modulator 24, detector 26 and optical

amplifier 28, as were identified in the embodiment of Fig. 1. A second detector 52 is positioned on leg 16a of coupler 16 in the manner of Bennett, U.S. Patent Application Ser. No. 09/481,159, to obtain a sample of the source 12 optical power that has not passed through the sensing region of sensor 50, i.e., polarizer 18, second coupler 20, coil 22 and phase modulator 24, as also described in Fig. 1. When appropriately delayed and modulated by a replica of the gyroscope signal, the sample of the source 12 optical power can be used to subtract the RIN, permitting further improvement of the ARW by increasing the signal power.

It can be understood that couplers 16 and 20, as well as couplers to be described hereafter, operate in a manner known in the art. A coupler may be attached to a first fiber such that the first fiber is coupled to a second fiber, the second fiber typically referred to herein as the legs of the coupler. A beam from the first or second fiber coming into the coupler from one direction is split into the first and second fibers upon exiting the coupler. Beams entering the coupler from both the first and second fiber combine/interfere with each other at the coupler and the combined/interfered beam is split into the first and second fibers upon exiting the coupler. As an example, coupler 16 can be attached to first fiber 14 to couple fiber 14 to a second fiber, or legs of coupler 16, one leg including detector 26 and optical amplifier 28 and the other leg (16a) including detector 52. The beams entering coupler 16 can combine/interfere and split as described, consistent with coupler operation as known in the art.

Referring back to Fig. 2, when an optical amplifier, such as optical amplifier 28 of Figs. 1 and 2, is used, spontaneous emissions can occur from both the front and back facets of the amplifier. The back facet output would also be received at second detector 52. Fig. 3 shows a fiber optic sensor 60 having an optical isolator 62 inserted between the coupler 16 and optical

amplifier 28. The isolator 62 passes the light traveling from the sensing region of sensor 60, i.e., polarizer 18, second coupler 20, coil 22 and phase modulator 24, to the detector 26 so that it can be amplified, while preventing the rear facet emissions of optical amplifier 28 from reaching the second detector 52.

If a sample of the spontaneous emission noise can be obtained from the optical amplifier 28, it too can be subtracted from the signal at the detector 26, in the manner suggested by Bennett in U.S. Patent Application Ser. No. 09/481,159. As there may be essentially no delay between the reception of the spontaneous emission at an auxiliary detector and reception of the signal at detector 26, and the spontaneous emission signal is not modulated, the process amounts to a direct subtraction. Such a signal can be obtained in fiber optic sensor 70 shown in Fig. 4.

Fiber optic sensor 70 has additional directional coupler 72 inserted between optical amplifier 28 and isolator 62, with third detector 74 positioned on leg 72a of third coupler 72, so as to receive signals from the direction of optical amplifier 28. By subtracting the signal received at third detector 74 from those at detector 26, the spontaneous emission signal from optical amplifier 28 may be eliminated from the signal at detector 26.

The combination of RIN reduction with optical amplification increases the potential improvement in ARW associated with optical amplification through the reduction of the RIN noise floor shown in Fig. 5.

The methods outlined herein can also be used in similar optical circuits which are used in conjunction with a Faraday effect current sensor, with the sensing element either a coil of sensing fiber or a reflective coil, e.g., as shown by Guido Frosio and Rene Dandliker,

"Reciprocal Reflection Interferometer for a Fiber-Optic Faraday Current Sensor," Applied Optics, Sep. 1, 1994, vol. 33, No. 25, pp. 6111-6122. Often in such circuits, the polarization maintaining fiber used to connect the sensing coil is longer than might be used in a low cost gyroscope sensor and the received optical power at the detector may be insufficient to achieve the desired sensitivity. Utilizing an optical amplifier in the manner shown, i.e., prior to the detector, can be an inexpensive method of overcoming the optical circuit losses.

While the embodiments have been described for optical circuits constructed from all-fiber components, the concept can be equally applicable to gyroscopes and current sensors employing integrated optical circuit chips in Lithium Niobate or other optical waveguide material, including concepts where the optical coil itself may be created on a substrate material. It can also be equally valid for signal processing concepts known as "closed loop", since the embodiments as described improve the signal to noise ratio at the output of the photodector.

It is known that many optical sources and optical amplifiers have a relatively strong preference for emission or amplification of one polarization rather than another. Generally, the preferred polarization can be selected to be the same as that which exhibits the minimum loss when transiting the polarizer associated with the gyroscope or current sensor optical circuit. It will be appreciated that the emissions in the unwanted polarization can contribute to the noise at each detector, without any corresponding benefit. For the highest performance, this energy should be precluded from reaching the photodetectors. This may preferably be accomplished by inserting polarizers 76, having minimum insertion loss in the desired polarization, immediately prior to each detector 26, 52, 74. Though illustrated in Fig. 4 only, it will be understood that polarizers 76 also can be inserted prior to detectors 26 and 52 of Figs. 1-3.

It is seen that the maximum optical power required at any point in the optical circuit of Figs. 1-4 can be minimized when compared with configurations not having optical amplifier 28, where all of the power may be generated at the optical source. This improves the reliability of the sensor while minimizing the product cost.

It can be appreciated that a semiconductor optical amplifier may be a broadband source of optical energy whose bandwidth may be typical of that desired for the sensor optical source. It follows that a semiconductor optical amplifier can be substituted for the conventional optical source and used with or without the optical amplifier 28, depending on the noise performance required. In applications where power levels may be low, optical amplifiers (not shown) also may be provided prior to detectors 52 and 74. Additional isolators (not shown) between these optical amplifiers and their respective couplers also may be provided.

While the invention has been disclosed in connection with the preferred embodiments shown and described in detail, various modifications and improvements thereon will become readily apparent to those skilled in the art. Accordingly, the spirit and scope of the present invention is to be limited only by the following claims.